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13. ABSTRACT (Maximum 200 words)

Speed and 'crosstalk' limitations, encountered by conventional metal transmission lines in 'chip to chip' data / information communication are overcome by Free Space Optical Interconnects (FSOI) for future ultra fast computing /communications systems. Fabry-Perot thin film Electrooptic(EO) modulators (STFP) function as high speed, low voltage operable optical interconnects. Development and demonstration of such STFP's based on ferroelectric/EO F-P modulators is described. For self tuning, with respect to F-P cavity Ferroelectric(FE) /EO thin film) thickness variations and consequent nonuniformity of extinction/contrast across STFP arrays, a holographic mirror (photorefractive LiNbO3) for compensation of thickness was used. For "proof-of -concept" demonstration, a PLZT bulk crystal plate was used for STFP arrays. A successful demo of 8x8 and 16x16 STFP interconnect arrays is described. The development of KTN (FE/EO) thin films on Sapphire substrates by RF-planar magnetron sputtering (for IC compatibility) and PLZT (low level of effort ,backup material) are described. Succesful FE properties observation in KTN and PLZT , materials characterization (structural and stoichiometric) and property evaluation are presented. The challenges presented in STFP applications are described. Deficiencies of K ,primarily due to negative ion resputterinf effects in KTN, Pb volatilization in PLZTand extraneous Pyrochlor phases are described.

14. SUBJECT TERMS

Free Space Optical Interconnects. Ferroelectric thin films, Electrooptic modulators, KTN, PLZT thin films.

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LOW VOLTAGE ,HIGH SPEED/CONTRAST ELECTROOPTIC THIN FILM DEVICES FOR FREE SPACE OPTOELECTRONIC INTERCONNECTS

FOREWORD: The requirement of ultra fast and high information density chip to chip communication for future generations of supercomputing and communications systems necccessitates new revolutionary devices for replacement of conventional metal transmission line interconnects. Transmission of electronic signals at light speed using Free Space Optical Interconnects (FSOI) based on suitable Electroptic (EO) Modulators offers advantages of a factor of four higher interconnect density, lower power consumption and elimination of 'crosstalk' between neighboring interconnects. For practical application, EO light modulators (EOLM) are desirable in thin film form for monolithic integration with other active semiconductor devices e.g. drivers,logic elements, detectors etc. Effficient, high contast light modulation of these thin film devices requires maximum permissible optical path length of the light beam in the EO medium for a high extinction ratio for low modulation voltages.This is enabled by Fabry-Perot (F-P) etalons of the EO film as modulators either in the reflection or transmission mode. In exploring suitable EO materials for thin films,besides the obvious preference for highest available EO coefficients, IC processing compatibility and optimum operation at room temperature must be considered. Accordingly, ferroelectric (FE) materials crystallizing in the Perovskite structure are very attractive. Comparison of relevant properties of bulk FE materials (single crystals and ceramics) revealed Potassium Tantalate Niobate (KTN) to show very high E-O effects. La modified Lead Zirconate Titanate (PLZT), although with smaller E-O effects than KTN , was also considered to be a good candidate for EOLM thin films. In an earlier, low level of effort preliminary /exploratory study of synthesis by RF-Planar magnetron sputtering, the authors had shown KTN and PLZT films to crystallize in Perovskite structure with good FE properties . EO response of such films (figure 1), indicated a nearly 70% higher quadratic response in KTN over PLZT films. At the start of this program virtually no information on the growth or characteristics of KTN films was available ; by comparison PLZT,PZT and a few other FE films synthesized by IC compatible processing had been widely reported. Inspite of this, due to its superior EO properties, KTN was chosen as the prime candidate for exploration/application, while PLZT was a lower level of effort 'backup' material. This work was motivated by the concept of "Smart Pixels" i.e. optical interconnect cells comprising of a thin film EOLM coupled with monolithic integrated logic/driver semiconductor elements on the same substrates; an array of such cells would constitute a FSOI. Figure 2 schematically shows a 'Smart Pixel'.

STATEMENT OF THE PROBLEM/APPROACH:

High uniformity,high contrast/extinction ratio F-P EOLM's: A fundamentally important consideration in the use of an array of F-P EOLM's as FSOI's arises from the thickness variation of EO films over the area of an array. Even small variations in the film thickness lead to

large variations in extinction/contrast ratios (via nonuniformities in the optical path lengths) of individual F-P cavity elements of an array and handicap the FSOI operation. A primary objective of the work reported concerned the problem of eliminating or compensating for the effects of such cavity thickness variation. Toward this end, an unconventional scheme was evolved for the 'Self Tuning' of a F-P EOLM with respect to thickness variation for high extinction ratios. Demonstration of 'proof-of concept' of a 'Self Tuned Fabry-Perot' (STFP) E-O modulator was the primary objective of this program. Development of FE/EO films,their characterization and evaluation for this application were associated goals.

In a conventional thin film F-P transverse EOLM, the film is sandwiched between top and bottom reflectors with the electric field applied between two electrodes normal to the incidence plane. The optical path length differences are reflected in the F-P fringe pattern variations. The STFP cavity uses a holographic mirror as the input reflector of the cavity. In the recording of the holographic mirror , cavity thickness nonuniformities are automatically compensated for. Recording the hologram is accomplished by illuminating the structure with a collimated laser beam. The volume hologram is optically recorded in place using the interference between the modulator illumination and the reflected output of the bottom mirror.The phase angle of the resulting hologram automatically compensates for optical thickness variations. The reflectivity of the recorded STFP,R_{STFP} can be expressed as :

$$R_{STFP} = \frac{\eta + R_m - 2\sqrt{\eta R_m}\,\sin(\phi)}{1 + \eta R_m - 2\sqrt{\eta R_m}\,\sin(\phi)} \qquad (1)$$

where η is the diffraction efficiency of the Bragg reflector, R_m is the rear mirror reflectivity and ϕ is the holographic phase parameter or the phase difference between the recording beam interference and the resulting refractive index interference patterns.The STFP reflectivity is independent of the cavity thickness.

Selection of FE-EO films for STFP applications : For STFP-EOLM application, besides a high E-O response,the FE material must have a Curie temperature (Tc) at slightly below room temperature (RT). If the EOLM is operated below Tc, in the FE phase, in addition to FE memory effects associated with hysterisis , fatigue due to repetitive field application can degrade performance of the device over time. Although large linear and quadratic EO effects are expected in the FE phase, the device may be optimally operated in the paraelectric phase at temperatures slightly higher than Tc (at or near RT) where a sufficiently large quadratic E-O effect is available. Among the few available FE materials suitable in this regard, KTN ($KTa_xNb_{1-x}O_3$,a solid solution of $KTaO_3$ and $KNbO_3$) has a Tc which can be continuously varied from 10 to 700 ^{0}K via its composition or the Ta: Nb atomic concentration ratio ; for $0.67 \leq x \leq 0.60$ the Tc varies from -25 to + 24 ^{0}C. Bulk KTN crystallizes in the Perovskite structure. However, in thin

films, depending on growth conditions (substrate temperature etc.) an extraneous "Pyrochlor" phase can appear in the Perovskite matrix.The presence of such a non FE Pyrochlor phase (of composition $K_2Ta_2O_6$), crystallizing in the cubic structure, can quench the FE /EO properties of the film. In addition, preservation of correct film stoichimetry i.e. an atomic concntration ratio K: Ta + Nb =1 is of critical importance for good FE properties. In KTN film growth , due to the higher volatility of K and lower bond strength with Oxygen, provision must be made for compensation of the expected 'K' deficiencies in obtaining any desired stoichiometry. Thus, Perovskite phase purity and correct stoichiometry are prerequisites for good FE/EO properties in the film.

For Monolithic ICs, processing compatibility and good epigrowth, R plane $(10\bar{1}2)$ Sapphire single crystals (for use with SOS devices) and Pt film coated Si were used as substrates. Films on Pt/Si substrates could be rapidly processed for parallel plate/sandwich capacitors. Due to previous demonstrations [1,2] of respectable quality film growth, RF-Planar Magnetron sputtering (RF-PMS) was chosen as the IC compatible deposition method. PLD (pulsed laser deposition), the alternative physical vapor deposition method considered, was insufficiently developed at the time of start of this program for serious consideration and is handicapped by the nonuniformities of film thickness and composition over even small areas. RF-PMS, on the other hand, can yield uniform films over relatively larger areas (nearly 2" diameter on the substrate with a 4" diameter target). However, in general, growth of RF-PMS of multicomponent oxide films and KTN in particular has its own drawbacks : (1) preferential sputtering yields of individual target constituents can be widely different. This is reflected in the film composition ; film stoichiometry differs from that of the target. (2) film resputtering by negative ions and secondary electron bombardment : during growth film cations (metallic constituents) are preferentially resputtered by negative oxygen ions originating from the target ; depending on its bond strength with film anions and mass, the weakest bonded cation (K in KTN) will be more deficient in the film than other metallic species from the target. In addition, at the high substrate (growth) temperatures ($\geq 680\ ^0C$) required for good crystallization, the "sticking coeffient " of K is expected to be lower than that of Ta or Nb. Generally, the Ta:Nb concentration ratio in the sputtering target is preserved in the film but K is seen to be deficient and yields undesirable film FE properties. Compensation of K, in principle, can be achieved by providing a greater than stoichiometric concentration of K in the sputtered flux via an excess of K in the sputtering target.

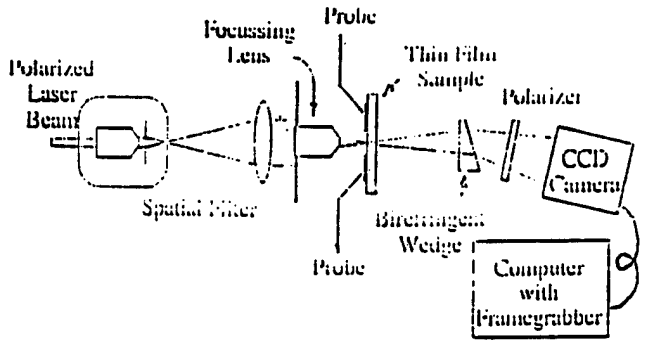
It should be noted that unlike many of the other widely used FE materials (Barium strontium Titanate, PZT, PLZT, $LiNbO_3$ etc.) KTN targets /ceramic discs are not commercially available even in small 1" diameter size. Of the fifteen plus US based commercial ceramics/target vendors, only three were willing to bid : mainly due to the lack of "knowhow" , the complexities, difficult crystal chemistry and ceramic processing of KTN. Of these three vendors, only one

vendor succeeded in supplying two 4" diameter targets which were used for demonstrating respectable E-O quality KTN films in an earlier program. Films of Figure 1 were from these targets. Soon after start of the program,reported here,this vendor essentially went out of business. Therefore,unforeseeably, it was neccessary to generate ('in house' at TRW) the technology for large (4" diameter) KTN ceramic target fabrication. While stoichiometric KTN ($KTa_xNb_{1-x}O_3$) pressed ceramic discs (greater than 90% theoretical density) can be made with some practice and relative ease, K rich targets ($K_{1+y}Ta_xNb_{1-x}O_3$ with $0 \leq y \leq 0.75$) are very difficult to fabricate. The difficulties can be understood by reference to the original Phase diagrams[3,4,5] for the KTN system.They are arise from : (1) the formation of an excess phase identified only as $3\ K_2O.(Nb,Ta)_2O_5$ .Very little is known about the properties of this phase except that it is very hygroscopic and crystallographically incommensurate with KTN. Hot pressing of this phase together with KTN yields only a limited fraction of theoretical pressed density (2) a little reported or understood solid state phase transition in the $K_{1+y}Ta_xNb_{1-x}O_3$ -K_2O system at $731\ ^0C \leq T \leq 1090\ ^0C$ for $0 \leq y \leq 0.75$. In conventional sintering/hot pressing a cold pressed ceramic compact is heated to as high a temperature (in a completely solid phase and with due regard to volatilization of constituents) as practically possible for good sintering and densification. Under these conditions when the K rich KTN compact is cooled from its sintering/ pressing temperature, the release of phase transformation energy at the solid state transition distroys intergrain bonding and overall mechanical integrity of the compact is lost by ceramic fracture or layering. Additionally, the larger the concentration of the K rich phase, the more hygroscopic/moisture sensitive does the overall target become and the lower is its integrity. A practical self limitation is thus set on the excess of K achievable in the target. At TRW a procedure utilizing novel ceramic processing methods (described in the next section) has been developed for the fabrication of such K rich targets.

In addition to the above considerations, the sputter deposition conditions will obviously influence the film stoichiometry and crystal structure. Some of these conditions are: sputtering gas (Ar) pressure, substrate temperature, RF power, target -substrate distance etc. For optimum FE/EO properties (derived from the structure and stoichiometry), the set of enabling growth evaluation conditions is empirically established by film deposition experiments. The effort to establish such a set, a study of basic materials characteristics (crystal structure and composition) and evaluation of the film properties and structure-property correlations constituted the E-O film development effort reported here. Although many of the findings have been previously reported in earlier semiannual reports[6], for reasons of continuity, some of them are briefly recalled in the next section.

MAJOR RESEARCH FINDINGS AND ACCOMPLISHMENTS

(1) Rapid Measurement of E-O Coefficient and Figure of Merit : For a direct and rapid E-O property evaluation , a simple but elegant method was developed. The method is based on the observation of differences in the ' Young's interference fringe patterns' from the E-O material with and without an applied electric field. A schematic of the experimental setup and its key features are shown in the accompanying diagram. The fully operational system was calibrated against well established standards and shows a better than 0.02^0 sensitivity for detection of phase retardation.



System Features:

- Currently 0.1° retardation change sensitivity: expect at least 0.02° sensitivity
- Any visible or NIR laser can be used
- Measurement speed limited by speed of detector array
- Bulk samples can be measured for calibration

Computer Functionality:

- Image from CCD is ~20 fringes
- Temporally averages intensities along 1 horizontal line
- Computes the Fourier transform of the line
- The phase at the peak frequency is the measured retardation

(2) 'PROOF -OF CONCEPT' Demonstartation of STFP'S : For demonstartion a polished PLZT (atomic.% concentartions=Zr:65,Ti:35,La:La+Pb=9) wafer (2 cms x .4 x .04 cms) was used as the E-O F-P cavity .A photorefractive, antireflection (AR) coated, y-cut single crystal $LiNbO_3$: Fe (5% mole fraction), was used as the holographic mirror and the rear/bottom reflector was a dielectric mirror. The PLZT was used as a bulk,transverse modulator. One half of the PLZT wafer was also AR coated and placed between the mirrors. The other half which was bare and had thickness variations from the crystal cutting/polishing operations was used to show thickness variations of the E-O cavity. The hologram was recorded with a spatially filtered,collimated 514 nm laser beam ; back reflected beams were 50:50 split before incidence to a CCD camera. Fresnel reflections from both sides of the uncoated bare wafer formed a low 'finesse' cavity. The back reflected images,without and with an applied voltage Vp (required for a shift by 1/2 fringe separation in the voltage 'off' state) for both the STFP (with holographic recording) and 'conventional' EOLM are shown in figure 3. Good uniformity contrast with and without an applied fields is clearly seen from the figure.

(3) STFP Modulator Array Demonstration : 8 x 8 and 16 x 16 arrays of STFP modulators were fabricated, using standard photolithography/microprocessing for electrodes, with PLZT optical polished wafers,photorefractive $LiNbO_3$:Fe single crystal holographic mirrors etc as in the above STFP domonstration. In addition, a conventional mirror mounted on a PLZT plate together with a lenslet array (for illuminating individual STFP elements with a 514 nm laser beam) were used. The

element spacing was 400 μm.Figure 4 shows the experimental setup.To simulate F-P cavity thickness variations and effects on reflection pattern, a voltage was applied to the pizoelectric PLZT plate by moving the conventional mirror with respect to the holographic mirror.Approximately 450 V was required to displace the mirror by one F-P fringe (514 nm). Figure 5 shows the backreflected image of the array ; each square corresponds to the image of one lenslet. Although the constrast in this preliminary device was somewhat low (due to the low diffraction efficiency of the hologram), excellent uniformity is seen between the nearly 11 x 13 modulators (all tuned to the same wavelength) of the 16 x 16 array. The white border seen around each square, in the "off" (correspoding to half wave retardation voltage Vp for the PLZT plate) state, is due to the lower diffraction efficiency of each elemental holographic mirror. A contrast ratio of ≅ 1.7 was measured.

(4) Fabrication of KTN Sputtering Targets: As mentioned in the previous section, the considerable difficulties of processing large (≥ 4" diameter) K rich ceramic discs (densified to ≥ 90% theoretical density) stem from the crystal chemistry and complexities of the KTN-K_2O phase equilibria. Consequently, KTN sputtering targets or laser ablation sources are not commercially available. Therefore, a ceramic process was developed 'in-house' at TRW for fabrication of targets.Targets with as much as a 40 atom % excess of K are now successfully fabricated. The process employs some unconventional methods.It proceeds as the following sequence:

(1) Low temperature Sol-Gel synthesis of starting fine grained KTN powders
(2) High temperature reaction with excess K_2CO_3 powders, multiple sintering,ball milling for homogenization, firing and cold pressing
(3) Laser welded encapsulation in stainless steel containers
(4) Hot Isostatic pressing within an empirically determined narrow range of temperatures (well below the "solidus" for the Phase diagram) and pressures for avoidance of solid state transformation during cooling.
(5) Extraction from encapsulant can, surface finishing and cold temperature epoxy bonding to metal backing plates.

Such targets with upto 40 at.% K excess are now successfully fabricated at TRW.

(5) Synthesis ,Characterization and FE/Dielectric Property Evaluation of KTN Films: In the search for 'best' deposition conditions by RF-PM sputtering for good FE/EO properties,the growth parameters varied were: target composition (K excess), sputtering gas (Ar) pressure, RF power, substrate temperature and geometry (target-substrate distance). As earlier mentioned, the main requirements for good FE quality films are : (1) crystallization in a purely Perovskite phase ; very little (≤ 5%) of the non FE, cubic Pyrochlor phase is permitted. (2) a KTN ($KTa_xNb_{1-x}O_3$)

stoichiometry with an atomic concentration ratio K:Ta+Nb= 1; the Ta:Nb ratio determines the film Tc. Operation of the film based device near RT requires $0.67 \leq x \leq 0.60$. The Ta:Nb ratio in the target is generally replicated in the film .In judging a film's suitability for further exploration , the films were characterized for basic materials parameters by :

(a) Film Crystal Structure : Structural characterization was done by Bragg x-Ray diffraction spectroscopy. Preferred Orientation (PO) of the KTN grains was measured as the ratio of integrated intensity of the dominant Bragg reflections to the total integrated intensity of all the peaks. Since the <100 > crystallographic direction is the 'polar' axis for Perovskite FE KTN, a 100% PO along the <100 > axis, as would be seen in good epitaxial growth on Sapphire and observed in many of the films of this work, was the most desired.

(b) Film composition (stoichiometry) analysis: Atomic concentration ratios of K : Ta:+ Nb and of Ta: Nb were measured by Rutherford Backscattering (RBS). He^{++} ions of nearly 2.27 Mev were used as the probe beam Comparisons of observed scatterd intensities with those of computer simulations provided the stoichiometry measurement.

Upon developing a KTN target fabrication process, a large number of deposition experiments were performed.Many of the findings were described in earlier semiannual technical reports [6] to ARO and , for brevity, only the major findings are reported here.

- In RF-PM sputtered films, independent of the sputtering power and pressure, films crystallize in pure Perovskite phase only above a substrate temperature of 730 ^{0}C as shown in figure 6 ; films crystallized at substrate temperatures between 590 to 730 ^{0}C are mixtures of materials crystallized in the Pyrochlor and Perovskite phases (Figure 7). With increasing temperatures from 590 to 730 ^{0}C, the fraction of Perovskite phase increases at the expense of the Pyrochlor phase. Below 590 ^{0}C, the films are essentially amorphous as shown by the Bragg reflection spectra.

- Only films deposited on Sapphire (Al_2O_3) substrates were analyzed for composition ; films on other substrates e.g. on Pt/Si substrates could not be definitively analyzed due to an overlap of substrate RBS peaks with those from the film. A typical RBS spectrum is shown in figure 8. According to these measurements, the films of this work showed Ta : Ta+Nb concentation ratios of 0.48 (severely K deficient) to 0.83 (moderately deficient). The extent of K deficiency was seen to depend on :

    - For any given sputtering gas (Ar) pressure , the higher the RF power, the greater is the K deficiency. The K deficiency is thought to arise mainly from negative ions (O^{--} ions) originating at the target . At high powers (or peak target voltages), the energetic O^{--} ions, not sufficiently retarded (thermalized) in traversing to the growing film by scattering from Ar, sputter film K ions preferentially and leading to their deficiency. Reducing the

RF power to a level where the glow discharge is barely sustained does indeed reduce the deficiency but yields unacceptably low deposition rates.

- For the same RF power, higher gas pressures result in a lowering of the K deficiency via reduction of resputtering negative ion energy.This is due to increased scattering and retardation of negative ions by Ar ions. However, at higher pressures, the deposition rates are substantially lowered. For the sputtering geometries used in this work, several hundred milliTorrs of Ar pressure would be required (for even low powers) to significantly suppress resputtering. Such pressures were beyond the capabilities of equipment used.
- For the same sputtering power and gas pressure, the higher the deposition (substrate) temperature,the higher is the K deficiency, although not as severe as due to the above two sources. This is thought to arise from the lower 'sticking coefficient' of adsorbed K on the substrate at high temperatures.
- Use of Oxygen (mixed with Ar) as a reactive sputtering gas for oxygen deficiency compensation, resulted in severe resputtering of the film. Severe K deficiency, a high density 'pinholes, large conical pits in the film and poor surface morphologies were seen.

Although good quality epitaxial films could be synthesized, negative ion resputtering of K from the films and consequent deficiencies remained a major challenge.

(6) Ferroelectric Properties Evaluation of Films: The primary FE properties of the film used in judging its quality was its Curie temperature behavior i.e. observation of a singularity or peak in its permittivity 'ε ' vs. temperature behavior and a nonlinear variation of permittivity with bias electric fields. Figure 9 shows such a Curie temperature plot for a representative film. The film was deficient in 'K' which is reflected in a substantially lowered peak permittivity from that of bulk single crystals (nearly 20,000 at 10 Khz). Figure (10) shows a plot of 'ε ' vs. dc bias field for a KTN film. The nonlinear variation, characteristic of its FE nature, is also clearly seen. Films with an appreciable K deficiency did not show a clearly defined peak in their permittivity ; instead 'ε ' was seen to rise continuously with temperature as shown in figure 11. This is believed to arise from the presence of a low permittivity 'space charge' layer due to Oxygen vacancies created during growth for charge compensation of K vacancies. Such a low capacitance layer in series with the high capacitance KTN film will mask (short out) the true KTN FE properties at near RT. With increasing temperature, the space charge layer, due to increased conductivity, would have a steadily diminishing effect on the net measured capacitance and will increasingly reflect the true large capacitance of the KTN layer at the measurment temperature. The presence of low permittivity Pyrochlor material in a largely Perovskite matrix would also have a similar effect.

Small capacitance Pyrochlor structure grains in series with large capacitance Perovskite grains will result in a low net capacitance measurement .

Unfortunately, even the best RF-PM sputtered KTN films, thus far, did not have sufficiently good optical properties (due to insufficient transparency and light scattering at surface inhomogeneities). Further property improvement/development will be neccessary before their insertion into an STFP EOLM's for demonstration.

(7) PLZT Film Synthesis and Properties : PLZT (9/65/35) films were deposited by RF-PM sputtering on R plane sapphire substrates. A triode sputtering geometry was used. In this configuration, the PLZT target/cathode and anode(grounded) are parallel and the grounded substrates are held close but parallel to the cathode/anode axis. In this "off axis" geometry, although direct bombardment of the growing film by negative ions and resputtering effects are reduced,the very low film deposition rates handicap practical growth efforts. In PLZT film growth at high temperatures (650-700 ^{0}C), loss of Pb by volatilization is a serious problem. Therefore these films were grown at a low temperature (200 ^{0}C) to retain the required Pb concentration and subsequently annealed at 800-850 ^{0}C in Oxygen for conversion to the Perovskite structure. This procedure also ensured the suppression of any Pyrochlor phase and the synthesis of fully Perovskite films. The FE properties ('ε ' vs.temperature and frequency) of a representative PLZT film are shown in figure 12. The E-O response of a PLZT film, with sureface electrodes in a transverse EOLM geometry, is shown in figure 13. The curve shows a quadratic E-O response and saturation at high voltages. Unfortunately, due to insufficient optical qualities and unstable properties, a STFP could not be fabricated from this film. Further improvement/ development of these films also will be neccessary before fabrication of a demonstrable array of STFP/smart pixels for FSOI's.

Conclusions and Suggestions for Further Research : The primary objective of this research, namely, the concept of a Self Tuned Fabry-Perot Electrooptic Light Modulator has been successfully proven/demonstrated. The associated basic objective of a 'proof-of -concept' and feasibility of operation of an array of such STFPs for Free Space Optical Interconnects was also successfully demonstrated. Although KTN films, previously largely unexplored, were also successfully synthesized and characterized to show good ferroelectric properties, their optical and E-O properties need further improvement before they can be inserted into an STFP array for a FSOI demonstration. A primary handicap of the RF-PM sputtered films was seen to be K deficiencies and stoichiometry deviations from the desired one in yielding sufficiently high E-O responses. This was due to negative ion resputtering effects. It is suggested that such K deficiency in RF-PMS can be suppressed by use of very high sputtering gas pressures ($\geq$ 200 Mtorrs; beyond the capability of our present equipment in this work) and low RF powers (while ensuring practical film growth rates). The development and use of sputtering targets with a larger excess of K (upto

60 at % excess over stoichiometry) than used in present work is also recommended for K deficiency compensation.

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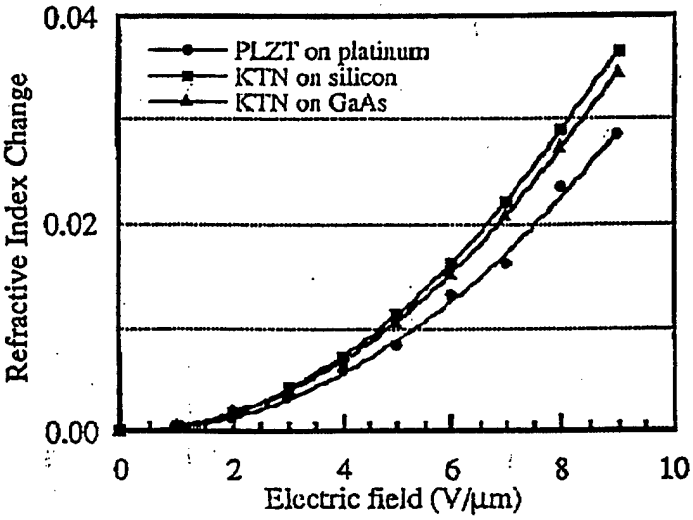
(10) Permittivity vs. bias field. of KTN films

(11) Permittivity vs.temp.of KTN film with significant K deficiency

(12) Permittivity vs.temperature .and frequency of PLZT

(13) Electrooptic response of a PLZT film



E-O Coefficient(Quadratic) :

0.5×10^{-16} m^2/V^2 for PLZT on platinum

0.85×10^{-16} m^2/V^2 for KTN on silicon

0.8×10^{-16} m^2/V^2 for KTN on GaAs

Figure 1

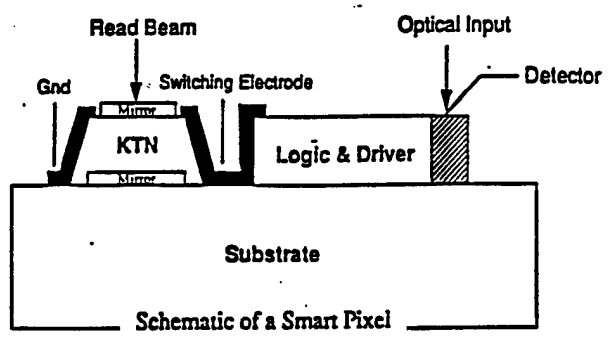
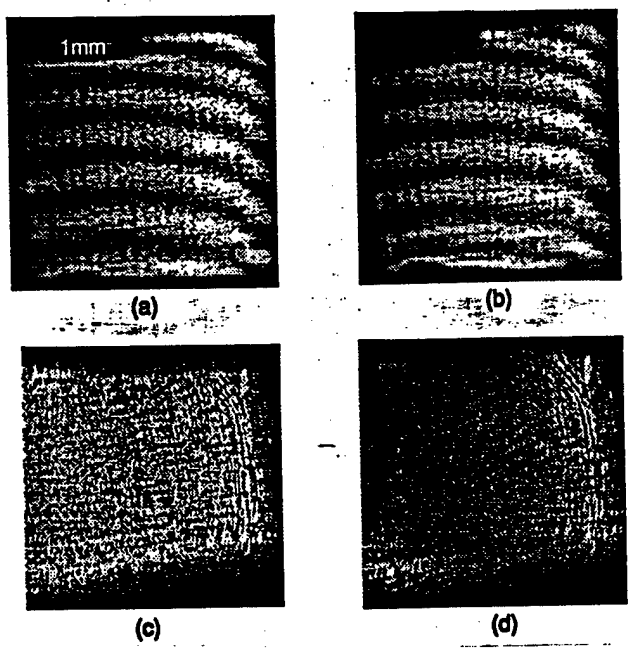
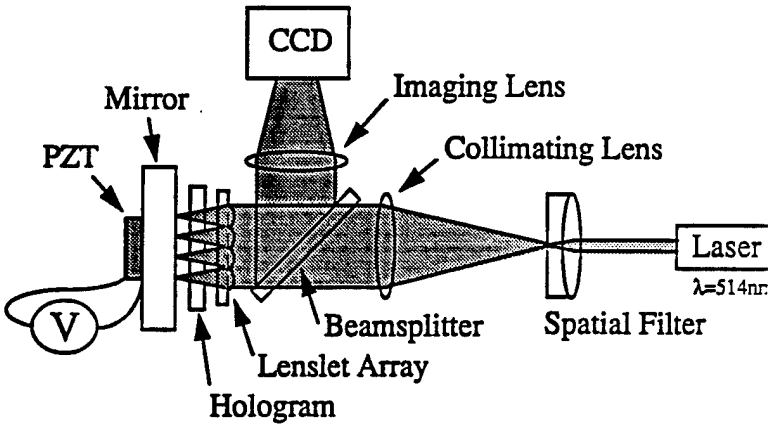


Figure 2



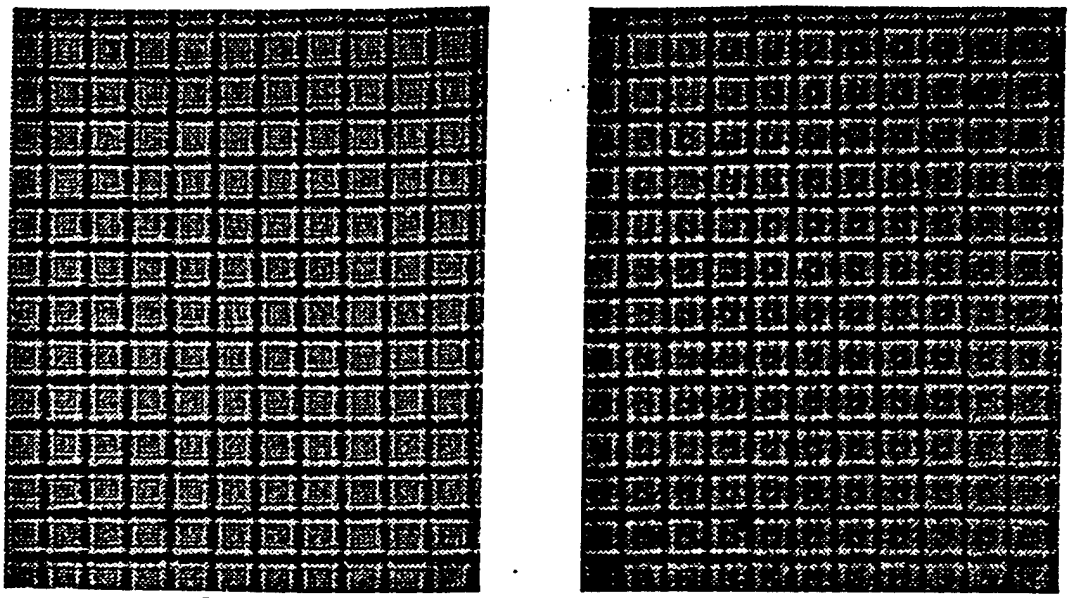
(a) and (b) are the backreflected images from the uncompensated modulator with 0 V/mm and 0.5 V/mm applied to the PLZT, respectively. (c) and (d) are the backreflected images from the STFP modulator with 0 V/mm and 0.4 V/μm applied to the PLZT, respectively.

Figure 3



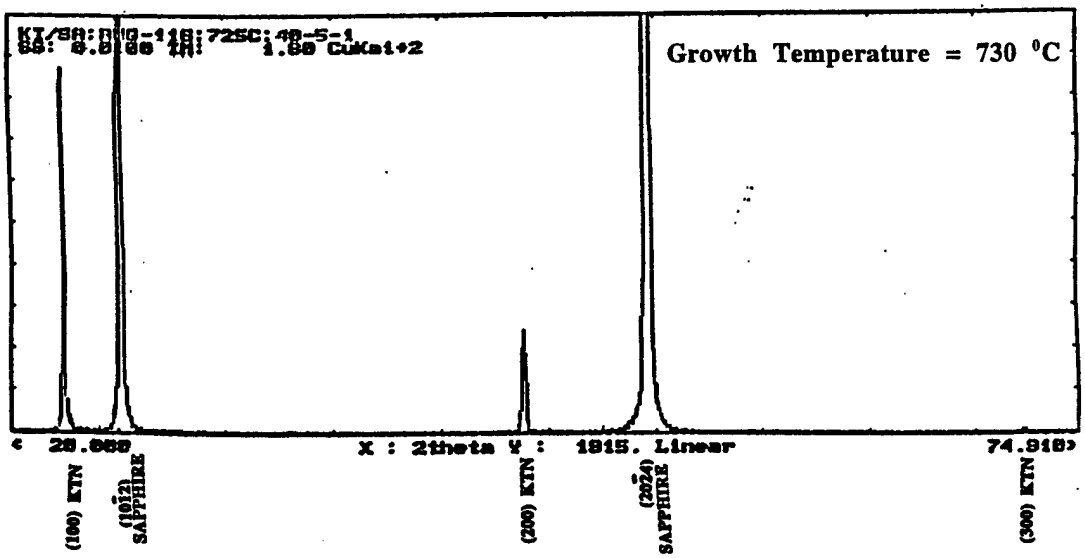
Experimental setup used for recording and operating the PLZT STFP modulator array.

Figure 4



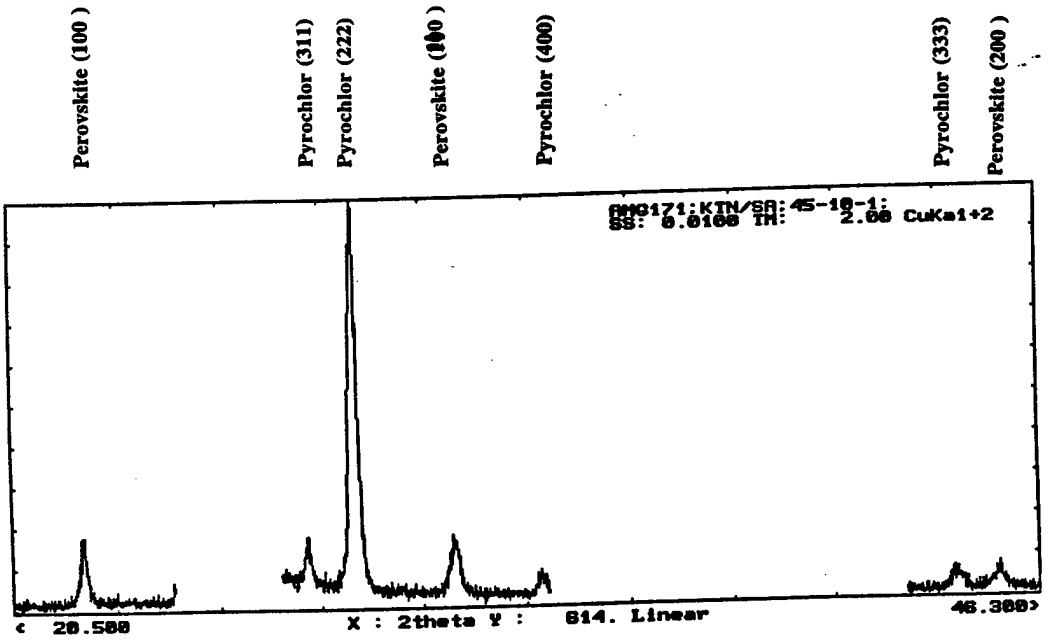
Preliminary reflection modulation results of the STFP array. The voltage refers to that applied to the PZT, which is used to change the cavity thickness.

Figure 5



ONLY 100 AND HIGHER ORDER PEAKS ARE SEEN;PREFERRED ORIENTATION ALONG POLAR 'C' AXIS
BULK SINGLE CRYSTAL LIKE EPITAXIAL GROWTH

Figure 6



KTN Film with mixed Pyrochlor and Perovskite phases. Growth Temperature = 620°C

Figure 7

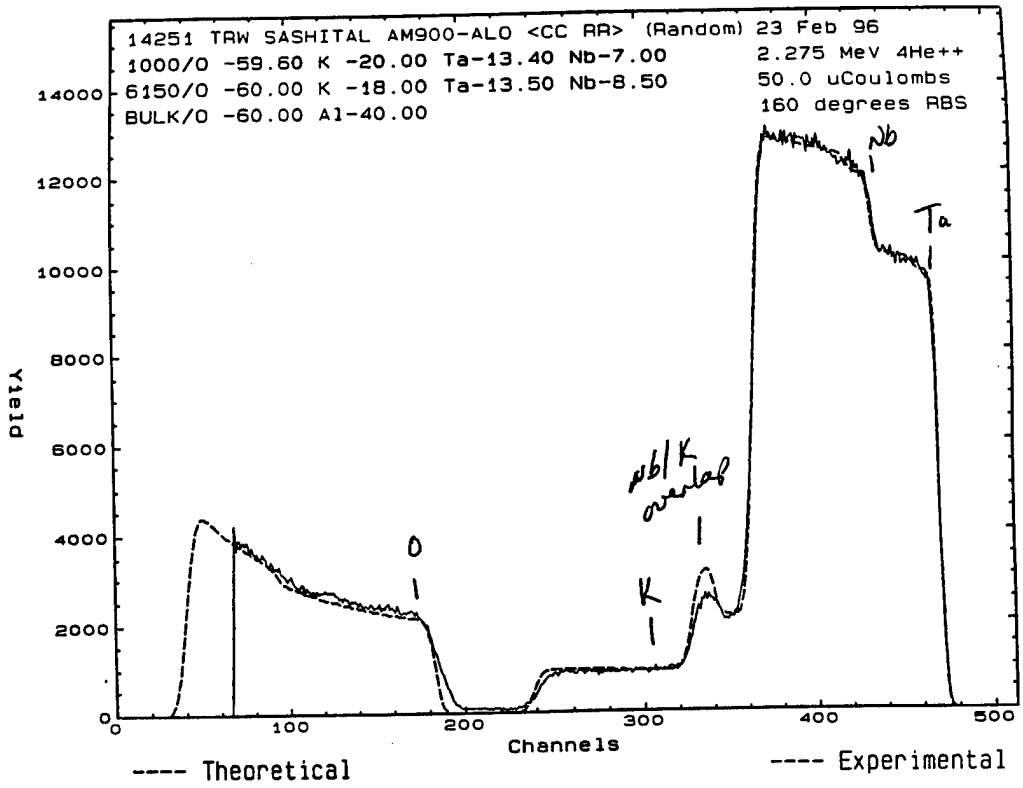
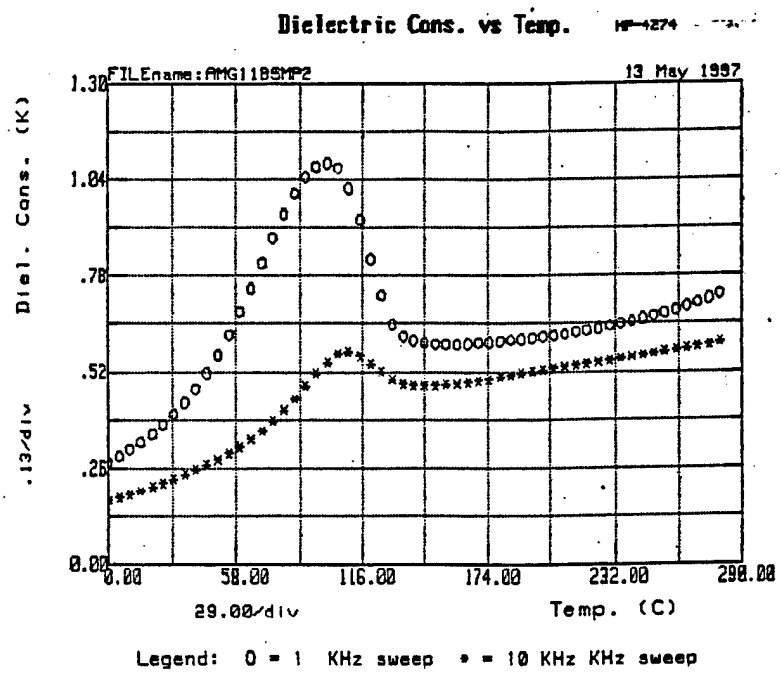
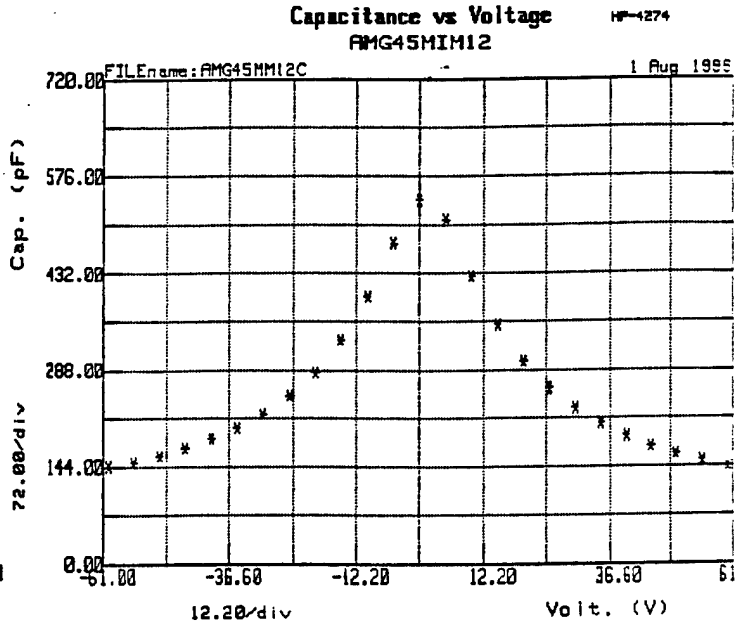


Figure 8



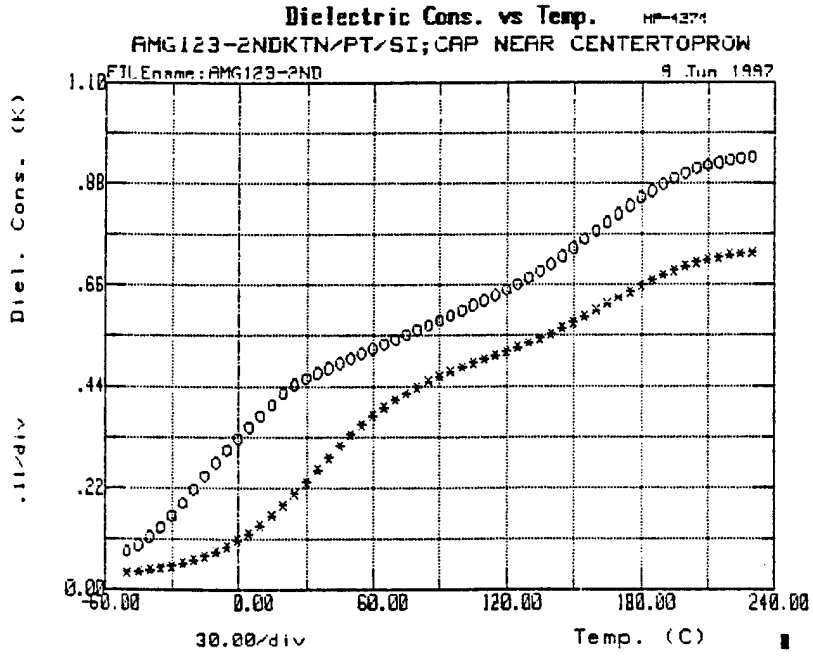
Permittivity vs. temperature of Nearly stoichiometricKTN films

Figure 9



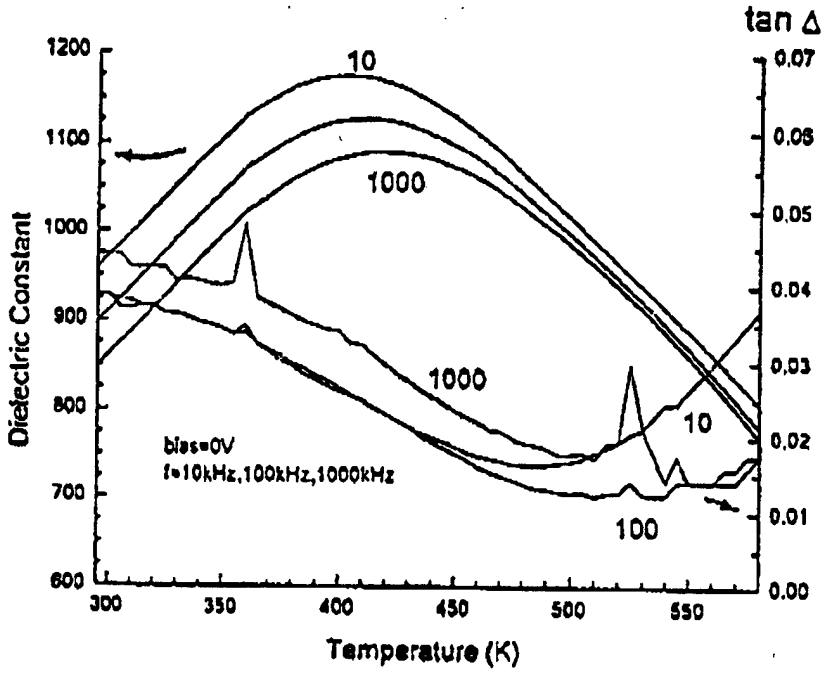
Permittivity vs. bias field. of KTN films

Figure 10



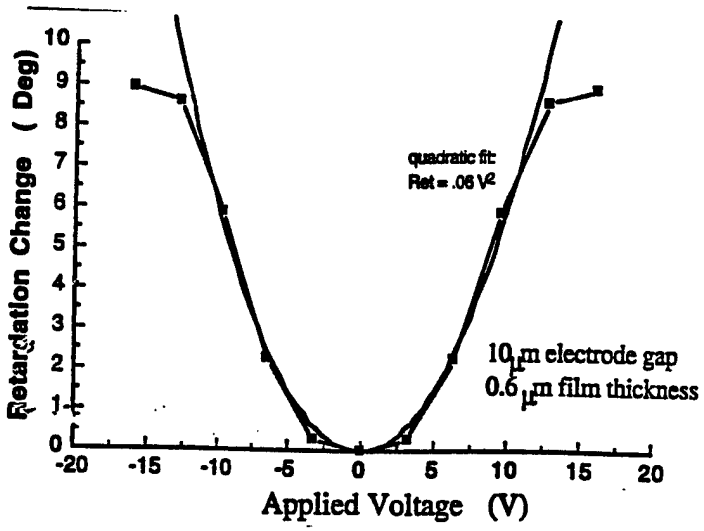
Permittivity vs.temperature ; KTN film with significant K deficiency

Figure 11



Permittivity vs.temperature .and frequency of PLZT film

Figure 12



Electrooptic response of a PLZT film

Figure 13

Low Voltage,High Speed & High Contrast
Electrooptical Thin Film Devices
for Free Space Optical Interconnects

Contract No: DAAHO4-93-C-0029 **TRW SN**: 60606

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LIST OF PUBLICATIONS

1) P. Harvey and S. Esener :Thickness Variation Compensation in a Fabry-Perot Modulator Array using a Self Tuned Fabry-Perot Structure, Appl. Phys. Lett., Vol. 70, pp1221-1223,1997.

(2) P. Harvey and S. Esener, "Compensation of Thickness Variations in a Fabry-Perot Modulator Array using a SelfTuned Fabry-Perot," OSA, Spatial Light Modulators and Applications, Technical Digest, Salt Lake City, Utah, 9, pp. 12-18, March 1995.

(3) B. Tunaboylu, P. Harvey, F. Deng, C. Fan and S. Esener, ìFerroelectric PLZT thin film deposited by RF triode magnetron Sputtering for spatial light modulators,î IEEE International Symposium on the Applications of Ferroelectrics, New Jersey, Aug. 18, 1996
(4) B. Tunaboylu, P. Harvey, F. Deng, C. Fan and S. Esener, ìThe Growth and Characterization of Epitaxial Lead Lanthanum Zirconate Titanate Thin Films on Sapphire, III. International Ceramics Congress, Istanbul, Turkey, Oct. 22, 1996